COLLISIONS OF FREE FLOATING PLANETS WITH EVOLVED STARS IN GLOBULAR CLUSTERS

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ABSTRACT

We estimate the rate of collisions between stars and free-floating planets (FFPs) in globular clusters, in particular the collision of FFPs with red giant branch (RGB) stars. Recent dynamical simulations imply that the density of such objects could exceed $\sim 10^6$ pc^{-3} near the cores of rich globular clusters. We show that in these clusters $\sim 5-10\%$ of all RGB stars near the core would suffer a collision with a FFP, and that such a collision can spin up the RGB star's envelope by an order of magnitude. In turn, the higher rotation rates may lead to enhanced mass-loss rates on the RGB, which could result in bluer horizontal branch (HB) stars. Hence, it is plausible that the presence of a large population of FFPs in a globular cluster can influence the distribution of stars on the HB of that cluster to a detectable degree.

Subject headings: globular clusters: general — globular clusters — stars: horizontal-branch — stars: planets

1. INTRODUCTION

Recent photometric and spectral observations of young star clusters have led to the discovery of many free-floating substellar objects, i.e., not in orbit with a star (Martín *et al.* 2001, and references therein). More recently, the microlensing survey of the globular cluster M22 (NGC 6656) has led to the *highly tentative* discovery of six free floating planets (Sahu *et al.* 2001). Intuitively, one would expect that low-mass objects, including free floating planets (hereafter FFPs), would be expelled from a globular cluster (GC) in a time much less than a typical age of GCs. Specifically, equipartition of energy between stars and planets would lead to planets with velocities well in excess of the cluster escape speed. However, recent numerical simulations (Fregeau, Joshi, & Rasio 2001; see also Hurley & Shara 2001) show clearly that FFPs can survive in GCs, with a substantial fraction of the original FFPs retained at the current epoch, and having a velocity distribution whose rms speed is only roughly twice that of the stars. The survival probability increases with GCs which have an initially higher central concentration. Fregeau et al. (2001) have shown that globular clusters with an initial mass fraction in FFPs of $\sim 20\%$ could evolve to the current epoch with an FFP population which exceeds the stellar population at the cluster center by a factor of ~ 100. If correct, this would lead to the obvious conclusion that the rate of collisions between FFPs and stars will be larger than the stellar collision rate by a similar factor (see discussion below). Since stellar collisions are generally non-negligible in GCs, as evident from the presence of a blue straggler population (Shara 1999), it is worth examining the possible influence of FFP-stellar collisions on the observed Hertzsprung-Russell (HR) diagram of GCs.

The collision between an FFP and star will have a much lesser effect than a collision with another star due to the fact that a planet will add very little mass and release only a small amount of gravitational energy. However, when entering the envelope of a giant star, whether on the red giant branch (RGB) or later on the asymptotic giant branch (AGB), FFPs may deposit a substantial amount of angular momentum, spinning-up the star by a factor of up to $\sim 100 \times (m_p/M_\mathrm{J})$, where m_p and M_J are the masses of the planet and of Jupiter, respectively. (The same comments apply to orbiting planets that are swallowed by the expansion of their parent RGB star; Siess & Livio 1999; Soker & Harpaz 2000). The faster rotation induced by the collision may lead to a higher mass-loss rate (Siess & Livio 1999; Soker & Harpaz 2000), and since RGB stars which lose more mass become bluer horizontal branch (HB) stars (e.g., Rood 1973; Catelan 1993; D'Cruz *et al.* 1996; Brown et al. 2001), planets may play a role in determining the distribution of stars on the HB of the HR diagram (Soker 1998a), the so-called HB morphology. Although the direct conenction between faster rotation and mass loss is not known, rotation appears to be the best candidate to enhance mass-loss rates in RGB stars (R. Rood, private communication).

Motivated by the above arguments, we have carried out a study to estimate the number of FFP-stellar collisions expected for stars that have evolved off the main sequence. In §2 we calculate the probability that a star in any evolutionary phase will collide with a planet. In §3 we calculate the average deposited angular momentum. We summarize our main results in §4.

2. COLLISION PROBABILITIES

The cross section for a FFP and a star to pass within a distance of closest approach, s, is given by:

$$\sigma = \pi \left[s^2 + \frac{2sG(M+m_p)}{v^2} \right], \tag{1}$$

where M and m_p are the masses of the star and the FFP, respectively, and v is the relative speed of the two objects when they are far apart (see, e.g., Rappaport, Putney, & Verbunt 1989; Di Stefano & Rappaport 1992). The first term in brackets is the geometrical cross section, while the second term represents the contribution from "gravitational focusing". For a star situated in a region containing a uniform space density, n_0, of FFPs, the rate at which a typical star will have an encounter with a FFP in which the distance of closest approach is smaller than s, hereafter referred to as the probability of a collision per unit time, $\dot{p}(s)$, is given by:

$$\dot{p}(s) \equiv \frac{dp}{dt} = \int_0^\infty n_0 f(v) \sigma(v,s) dv, \tag{2}$$

where we have averaged the velocity-dependent cross section over the appropriate relative speed distribution, $f(v)$, between stars and FFPs. If we assume that $f(v)$ can be represented by a Maxwell-Boltzmann distribution with a 1-dimensional rms relative speed of v_0, then equation (2) reduces to:

$$\dot{p}(s) = 2n_0(2\pi)^{1/2} \left(s^2 v_0 + \frac{sGM}{v_0} \right) \tag{3}$$

(see equation 3.4 of Di Stefano & Rappaport 1992), where we have neglected the mass of the planet in comparison with the stellar mass.

We now assume that a collision will take place if the distance of closest approach s is smaller than the stellar radius R. For stars of mass $\sim 1\ M_\odot$ and radius $R \lesssim 3\ R_\odot$, the approaching planet will disintegrate due to tidal forces, while for larger stellar radii, the planet will strike the stellar surface intact. However, even for the case of tidal breakup, we expect the planetary debris to strike the star if $s \lesssim R$, and thereby transfer all of its orbital angular momentum.

In order to compute the probability of a planet-star collision, we need to know how much time the star spends at each stellar radius interval during its lifetime. Since stars of mass $0.8 \lesssim M \lesssim 2\ M_\odot$ follow the well-known core mass–radius and core mass-luminosity relations (Refsdal & Weigert 1970, 1971; Rappaport *et al.* 1995; Eggleton 2001) once they have entered the giant phase, it is straightforward to derive an approximate analytic expression for the "dwell time", dt, for a star anywhere beyond the subgiant phase to be found with radius between R and $R + dR$:

$$\frac{dt}{dR} \simeq FR^{-2}, \tag{4}$$

where we estimate the constant to be $F \simeq 3 \times 10^{27}$ s cm (see also Webbink, Rappaport, & Savonije 1983). We estimate that the power-law dependence on R given in eq. (4) is accurate to ± 0.2 in the

exponent. We then set $s = R$ in equation (3) above, and multiply both sides by dt/dR to produce a collision probability (with a planet) per unit radius interval of the evolving star. The result is:

$$\frac{dp}{dR} \simeq 2n_0(2\pi)^{1/2} F\left(v_0 + \frac{GM}{v_0 R}\right). \tag{5}$$

If we now integrate equation (5), we find

$$p \simeq 0.029\left(\frac{n_0}{10^6\ \mathrm{pc}^{-3}}\right)\left[0.25\left(\frac{R_2 - R_1}{100R_\odot}\right)\left(\frac{v_0}{20\ \mathrm{km\ s}^{-1}}\right) + \left(\frac{v_0}{20\ \mathrm{km\ s}^{-1}}\right)^{-1}\ln(R_2/R_1)\right] \tag{6}$$

where we have taken the stellar mass to be $0.85M_\odot$, and normalized the 1-dimensional rms relative speed between planets and stars to 20 km s^{-1}. This is the probability that a planet–star collision will take place while the star expands from radius R_1 to R_2. Since equation (4) really applies to the subgiant phase and beyond, the results given in equation (6) are most accurate for low-mass stars with $R \gtrsim 3R_\odot$. Equation (6) implies that there is a $\sim 7\%$ probability for a star to collide with a planet sometime during the star's growth from 10 to 100 $R_\odot$. This probability is obviously sensitive to the normalization value for the density of planets, $n_0 = 10^6$ pc^{-3}. For substantially lower planet densities the probability becomes negligible, while for somewhat higher densities the probability can be rather appreciable.

Repeating the same calculation for main sequence stars of $M = 0.85M_\odot$ and $R = 0.8R_\odot$, we find that the probability for the star to collide with a FFP during its 10^{10} yr main-sequence life is $\sim 18\%$. This shows that collisions of FFPs with main sequence stars in Galactic globular clusters will not deplete the FFP population much. Note also that the collisions will not deposit as significant an amount of angular momentum as in the case of an RGB star (see next section). The probability that a HB star, with a life span of $\sim 10^8$ yr, will suffer a FFP collision is only $\sim 1\%$ (for $n_0 = 10^6$ pc^{-3}).

Recent numerical simulations of globular clusters by Fregeau *et al.* (2001) clearly demonstrate that a substantial fraction, $20 - 80\%$, of FFPs can survive to the current epoch. This study also shows that the density profile of FFPs evolves rapidly during the early history of the cluster (i.e., in the first 5×10^8 yr), and then approaches a well-defined asymptotic structure at the current epoch with the ratio of planets to stars increasing dramatically with radial distance from the cluster center. For model clusters of moderate initial central concentrations, Fregeau et al. (2001) find that for a current mass fraction in FFPs of $\sim 10\%$ (for the entire cluster), the central density in planets (each of mass $0.25M_\mathrm{J}$) would be $\sim 2 \times 10^5$ pc^{-3} at the current epoch. However, if we consider the 'top 20' non-core-collapse globular clusters in terms of their central stellar densities (Harris 1996), we estimate that such clusters could plausibly have central planetary densities of $\sim 10^6$ pc^{-3}. We adopt this somewhat optimistic normalization value for n_0; thus, our results will pertain more to the richer, non-core-collapsed clusters.

3. DEPOSITION OF ANGULAR MOMENTUM

At the distance of closest approach, s, the planet's velocity and specific angular momentum are $v = v_0[1 + (R_b/s)]^{1/2}$ and $j = sv_s$, respectively, where

$$R_b \equiv \frac{2GM}{v_0^2}. \tag{7}$$

The collision rate per unit interval in s for a star of radius R to engulf a planet with closest approach s is given by $d\dot{p}/ds$. From equation (3) we find:

$$\dot{p}' \equiv \frac{d\dot{p}}{ds} = 2n_0(2\pi)^{1/2}v_0(2s + R_b/2). \tag{8}$$

The average specific angular momentum per collision for a star of radius R is

$$j_{\rm ave} = \frac{1}{\dot{p}(R)}\left(\int_0^R \dot{p}' j ds\right), \tag{9}$$

which, when written out, is:

$$j_{\rm ave} = \frac{v_0}{R^2}\left(1 + \frac{R_b}{2R}\right)^{-1}\int_0^R \left(2s + \frac{R_b}{2}\right)\left(s^2 + sR_b\right)^{1/2} ds. \tag{10}$$

Integration of equation (10) yields the average specific angular momentum deposited in stars with radius R:

$$\frac{j_{\rm ave}}{v_0 R} = (24 + 12a)^{-1}\left[\sqrt{1+a}\;(16 + 10a - 3a^2) + 3a^3 \ln\frac{1 + \sqrt{1+a}}{\sqrt{a}}\right], \tag{11}$$

where $a \equiv R_b/R$. A simple useful approximation to equation (11) can be obtained if we note that for our canonical values, $v_0 \lesssim 20$ km s^{-1}, $M \gtrsim 0.85M_\odot$ and $R \lesssim 100R_\odot$, we have $a > 8$. We then carry out a Taylor-series expansion of equation (11) in the variable $1/a$ and keep only the leading term:

$$\left(\frac{j_{\rm ave}}{v_0 R}\right)_{a\gg 1} \simeq \frac{2}{3}a^{1/2}. \tag{12}$$

The maxium specific angular momentum a FFP can deposit into a star with radius R is obtained for $s = R$ and it is

$$\frac{j_{\rm max}}{v_0 R} = (1 + a)^{1/2}. \tag{13}$$

These values should be compared with the specific angular momentum deposited by an orbiting planet. Because of tidal interactions, the envelope of RGB stars will engulf stars having an orbital

separation of $r \sim 4R$ (Soker 1998a). The specific angular momentum of an orbiting planet is therefore

$$\frac{j_{\rm orb}}{v_0 R} = (2a)^{1/2}. \tag{14}$$

The values of angular momentum, J, implied by equations (11) – (14) as functions of the stellar radius R are plotted in Figure 1 (solid, dotted, dashed-dotted, and dashed, lines, respectively) as $J = jM_{\rm J}/J_{\odot}$, where $J_{\odot}$ is the present angular momentum of the Sun $\sim 1.7 \times 10^{48}$ g cm^2 s^{-1}. These units facilitate direct comparison with commonly used values. Therefore, the values on the graph crudely indicate the factor by which the planets will spin up the star they collide with, with R being the radius of the star at the time of the collision. From the graph we see that FFPs can spin up RGB stars by a factor of up to ~ 50, with an average factor, over all collisions in all RGB stars, of ~ 20 (marked on the graph by a short horizontal line marked $J_{\rm coll}$). We now derive this value.

In equation (11), an approximation of which is given in eq. (12), we derived the average specific angular momentum deposited in stars for which the collisions take place when the stars have radius R. However, the stars have a continually evolving radius. Therefore, of somewhat greater interest is the average specific angular momentum deposited in stars as they evolve from R_1 to R_2:

$$j_{12} = p^{-1} \int_{R_1}^{R_2} \frac{dp}{dR} j_a(R) dR, \tag{15}$$

where dp/dR is given by equation (5) and p by equation (6). If we approximate the expressions for dp/dR and p by using only the "gravitational focusing" portion of each one (last terms in equations (5) and (6)), and utilize the approximate expression (eq. 12) for j_a, we can integrate equation (15) to find the following simple expression:

$$\frac{j_{12}}{v_0 R_2} = \frac{4}{3} a_2^{1/2} \left[\frac{1 - (R_1/R_2)^{1/2}}{\ln(R_2/R_1)} \right], \tag{16}$$

where $a_2 \equiv 2GM/v_0^2 R_2$. For the typical case we are considering, the "gravitational focusing" term dominates, i.e., $a_2 >> 1$, the quantity in brackets varies only between 0.30 and 0.42 for R_2/R_1 ranging between 10 and 2.

We can now utilize equation (16) to estimate the average angular momentum, $J_{\rm coll}$ that would be injected into the stellar envelope of a giant by the time it reaches the tip of the RGB if there has been a collision with a planet:

$$J_{\rm coll} \simeq 0.5 a_2^{1/2} v_0 R_g m_p = 0.7 m_p (G M_g R_g)^{1/2}, \tag{17}$$

where M_g and R_g are the mass and radius of the star at the tip of the giant branch, respectively, m_p is the mass of the colliding planet, and R_2 in equation (16) has been set equal to R_g. Note that equation (17) is independent of v_0. Finally, we can estimate the factor by which colliding

FFPs enhance the angular momentum of giant envelopes over and above their nominal angular momentum, which we take to be of order $J_\odot$:

$$\frac{J_{\rm coll}}{J_\odot} \simeq 22 \left(\frac{m_p}{M_{\rm J}}\right) \left(\frac{R_g}{100 R_\odot}\right)^{1/2}, \tag{18}$$

where we have taken $M_g = 0.85 M_\odot$. The value of the leading coefficient in eq. (18) is plotted in Fig. 1 as a reference. For giants in globular clusters the angular momentum is likely to be factors of several times lower than $J_\odot$ (see, e.g., Sills & Pinsonneault 2000) due to angular momentum losses on the main sequence as well as on the giant branch. This would make the enhancement factor expressed in eq. (18) somewhat larger. If on the other hand, we had normalized the results to Saturn-like planets, the net enhancement factor would remain roughly as given by eq. (18).

4. SUMMARY AND CONCLUSIONS

We have shown that if the cores of rich globular clusters have free-floating planet densities of $\sim 10^6$ pc^{-3}, that $\sim 5-10\%$ of all RGB stars in the core would suffer a collision with such an FFP. Such collisions would, on average, increase the rotational angular momentum of the RGB star by more than an order of magnitude (see eq. 18). We speculate that the greatly enhanced rotation rates may lead to enhanced mass-loss rates during the RGB phase (Siess & Livio 1999; Soker and Harpaz 2000).

To help quantify the importance of the collision-induced angular velocity of the RGB stars, we compare it with the Keplerian angular velocity at its equator. Since most of the angular momentum of the spun-up RGB star is in its envelope, we take $J_{RGB} = I_e \omega$, where ω is the solid-body angular velocity (a good assumption in the convective envelope), and I_e is the envelope's moment of inertia $I_e = \alpha M_e R_g^2$, where M_e is the envelope mass and $\alpha \simeq 0.1$ (Soker & Harpaz 2000). Thus, if we equate the envelope angular momentum to the value of $J_{\rm coll}$ given in equation (17), we derive the spun-up RGB angular velocity in the form

$$\frac{\omega}{\omega_{\rm Kep}} \simeq 10^{-2} \left(\frac{m_p}{M_{\rm J}}\right) \left(\frac{M_e}{0.4 M_\odot}\right)^{-1} \left(\frac{\alpha}{0.1}\right)^{-1}, \tag{19}$$

where $\omega_{\rm Kep} = (G M_g / R_g^3)^{1/2}$ is the Keplerian angular velocity of an orbit on the stellar equator, and we took $M_g = 0.85 M_\odot$.

Although the above value of $\omega/\omega_{\rm Kep}$ seems small, it may actually be quite significant. First we note that presently the sun has $\omega/\omega_{\rm Kep} = 4.5 \times 10^{-3}$, and shows axisymmetric rather than spherically symmetric surface activity. This means that the magnetic field dictates the activity, including the solar wind properties. In RGB and AGB stars, it is radiation pressure (acting on grains) rather than magnetic activity that dictates the wind properties. However, due to the strong convection in RGB and AGB envelopes magnetic activity is expected, despite the very

slow rotation. Any increase in the slow rotation rate may significantly enhance surface magnetic activity to a level where cool magnetic spots can be formed. Dust formation, hence mass-loss rate, is supposedly enhanced above these cool spots. The fact that most planetary nebulae have axisymmetrical rather than spherical structure, but not all of these have binary star companions, hints that slow rotation can indeed dictate some properties of the mass loss process. Based on a crude estimate, Soker (1998b) argues that rotation velocities of $\omega \gtrsim 10^{-4}\omega_{\rm Kep}$, are sufficient to lead to magnetic activity which may form cool magnetic spots on the surface of AGB stars. If this holds for RGB stars, then even planets much lighter than Jupiter may influence the mass loss process. The more mass the star loses on the RGB the bluer the HB star it becomes.

Hence, our main claim in the present paper is that the presence of a large population of FFPs in a GC can lead to a potentially significant population of blue, and extreme blue, HB stars.

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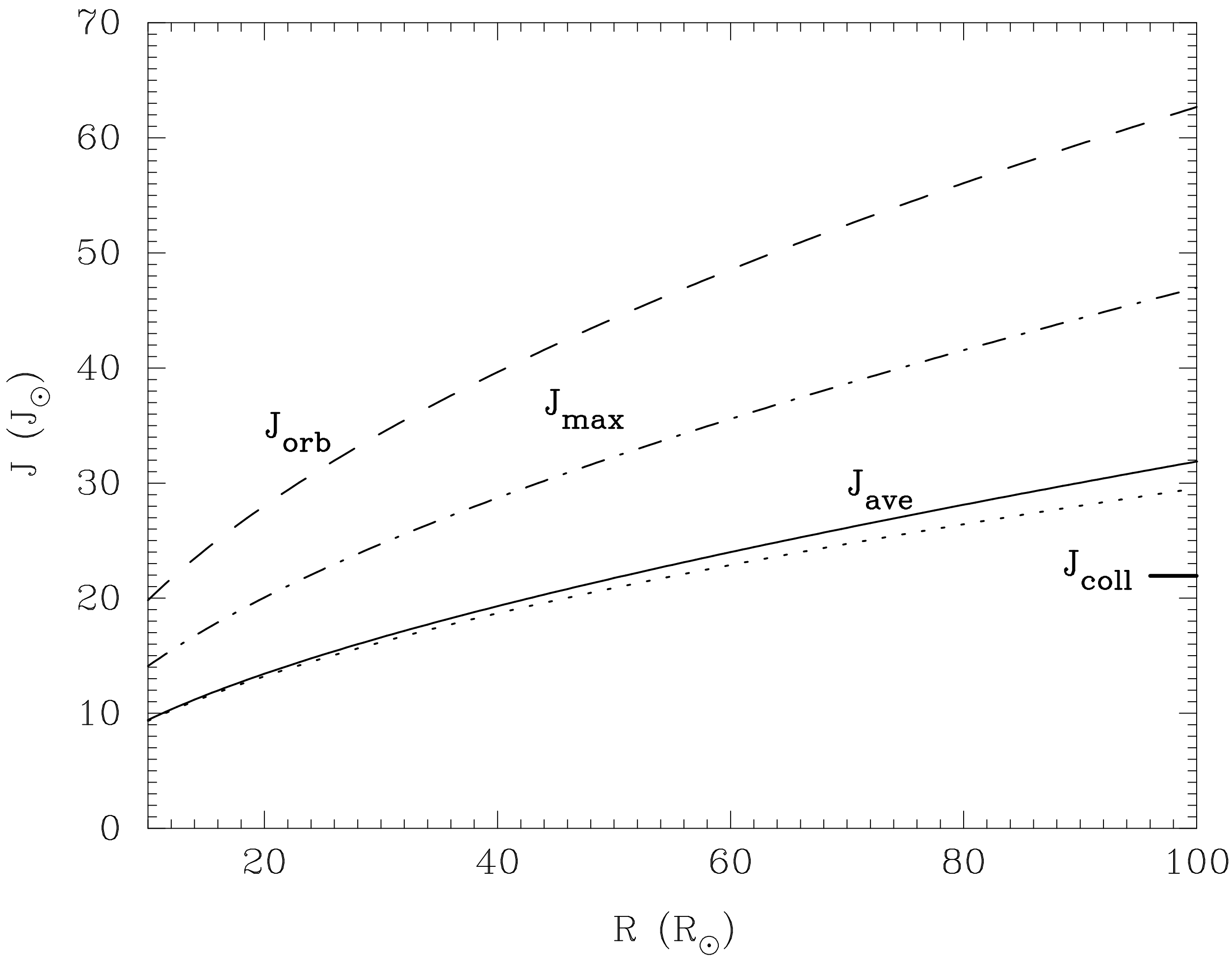

Fig. 1.— Planet-deposited angular momentum, in units of the solar angular momentum 1.7×10^{48} g cm^2 s^{-1}, as a function of the RGB stellar radius at the time of collision. Plotted are the average angular momentum deposited by FFPs, $J_{\rm ave}$: "accurate" expression (eq. 11; solid line), and an approximate expression (eq. 12; dotted line); maximum angular momentum deposited by a FFP, $J_{\rm max}$ (eq. 13; dot-dashed line); and angular momentum deposited by an orbiting planet, $J_{\rm orb}$, which is engulfed due to tidal forces when the parent star expands to $\sim 1/4$ of the orbital separation (eq. 14; dashed line). All calculations assume a planetary mass equal to that of Jupiter, $M = 0.85 M_\odot$, and $v_0 = 20$ km s^{-1}. Also marked ($J_{\rm coll}$) the average deposited angular momentum over all collisions in all RGB stars, assuming the RGB terminates at $R = 100 R_\odot$ and $m_p = M_{\rm J}$. Jupiter's orbital angular momentum is 1.93×10^{50} g cm^2 s^{-1}, about 100 times that of the sun, so values in the plot are approximately the *percentage* of Jupiter's orbital angular momentum.